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ABSTRACT

Grain yield of cereal crops is closely associated to the aerial (above ground) dry matter yield, but predictions of grain yield based on model estimates of dry matter yield are often inaccurate due to variations in the assumed harvest index. This study analyzed the relationship between grain yield and aerial dry matter yield from published studies for winter wheat [*Triticum aestivum* (L.)] and grain sorghum [*Sorghum bicolor* (L.) Moench] conducted at Bushland, TX in the Southern High Plains. Harvest index (*HI*) was defined and determined as the slope of the linear relationship between Y_d, plant grain yield in Mg ha^{-1} on a dry basis, and *DM*, aerial (field) dry matter yield in Mg ha^{-1}, as contrasted to the traditional definition of *HI* as the ratio Y_d/DM. Simple linear relationships had coefficients of determination of 0.95 for the seven grain sorghum experiments and 0.75 for the five winter wheat experiments at Bushland and standard errors of the estimates of 0.47 Mg ha^{-1} and 0.63 Mg ha^{-1}, respectively. The *HI* of winter wheat and grain sorghum at Bushland was 0.35 and 0.47, respectively, and largely unaffected by fertility, water use, row spacing, and many other cultural practices like tillage and profile modification, and growing season environment. The linear regressions indicated a significant (0.05 probability level) intercept value of −0.53 Mg ha^{-1} for grain sorghum while the intercept value 0.16 Mg ha^{-1} for winter wheat was not significant (0.05 probability level).

Dry matter production of many crops has been demonstrated to be related to transpiration (de Wit, 1958) and radiation interception (Monteith, 1977). These two relationships or some modification of them are used in most of the current crop growth models to predict dry matter yield. Tanner and Sinclair (1983) and Versteeg and van Keulen (1986) present two different methods to estimate dry matter production for crops. Both indicated the difficulty in reliably estimating the grain yield based on the dry matter yield.

Donald (1962) proposed the term harvest index (*HI*), defined as the ratio of grain yield (dry basis) to aerial dry matter yield, to quantify the crop dry matter partitioning into economic yield components for breeding advances. Donald and Hamblin (1976) reviewed the utility of the harvest index concept in relation to agronomic improvements in crop yields. Snyder and Carlson (1984) reviewed partitioning for crop yield improvements. These reviews proposed many concepts related to the harvest index that included the following hypotheses: (i) *HI* is a conservative species-related parameter, (ii) *HI* has been improved through breeding, and (iii) *HI* is directly related to photosynthetic partitioning into the economic yield components.

Gardner and Gardner (1983) reported the robust nature of the linear relationship between the plant grain yield (y_d in g plant^{-1} on a dry basis) and the plant aerial dry matter (d_m in g plant^{-1}) for several species. They emphasized the importance of the offset in terms of dry matter necessary before any grain was produced. They proposed the following equation

$$y_d = C\,(d_m - d_o) \qquad [1]$$

where d_o is the intercept of the relationship on the abscissa representing the hypothetical minimum plant size that produces grain in g plant^{-1} and C is the slope representing the linear increase in grain yield per unit dry matter yield increase. Although Gardner and Gardner (1983) emphasized that neither C nor d_o were "fixed" or "unchangeable", they stated that examination of many sets of data showed the relationship expressed by Eq. [1] to be "remarkably robust." Although they did not define C as the harvest index, clearly the two are related, at least qualitatively. The relationship between field grain yield (Y_d in Mg ha^{-1}) and aerial field dry matter yield (*DM* in Mg ha^{-1}) is the product of the plant density (*PD* in plants ha^{-1}) times Eq. [1] given as the following

$$Y_d = C'\,(DM - DM_o) \qquad [2]$$

where C' is the slope of the linear relationship between Y_d and DM and DM_o (dry matter threshold) is the intercept in Mg ha^{-1} on the abscissa representing the minimum field dry matter yield necessary for grain yield given as

$$DM_o = 10^{-6}\,PD\,d_o \qquad [3]$$

Equation [3] indicates the expected linear effect of plant density on the field dry matter yield threshold (DM_o). If plant density is constant, then both Eq. [1] and [2] should be the same with identical slopes (C and C', respectively). However, if plant density is a variable, then C would not necessarily equal C'. Equation [1] should be independent of plant density while Eq. [2] will be dependent on plant density. However, accurate determination of d_o in Eq. [1] by linear regression will be difficult unless the plant density variation is unusually large to permit data values for plant grain yields to be near zero in order to determine the true value of the abscissa intercept, which may well be statistically insignificant in many cases.

Several investigators have reported regression analyses between Y_d and DM with significant offset values (D_o). [See Aase and Siddoway (1981) and Slabbers et al., (1979).] Linear relationships between Y_d and DM with any abscissa offset lead to curvilinear relationships between Y_d/DM (the *HI* ratio) and *DM*. This partially explains the poorer linear correlations reported between Y_d/DM and *DM* and the better linear correlations between Y_d/DM and Y_d (Donald and Hamblin, 1976). Figure 1 illustrates this concept with the linear relationship (Y_d vs. *DM*) for grain sorghum from Slabbers et al. (1979). If the offset (DM_o) is significant, then the *HI* ratio (Y_d/DM) is not conserva-

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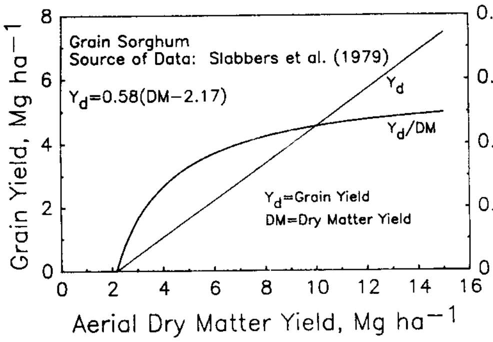

Fig. 1. Illustrations of grain, dry matter yield relationships for grain sorghum using linear regression lines from Slabbers et al. (1979).

tive, especially at low values of DM, but does approach asymptotically to a constant value at higher levels of DM. In terms of partitioning of DM into grain, the constant value of the slope implies equal grain yield increases for each increment of dry matter produced above DM_o.

The purposes of this paper are to: (i) examine the characterization of the relationship between grain and dry matter yield on a field basis for winter wheat and grain sorghum in the environment of the Southern High Plains, (ii) demonstrate the utility and conservative nature of the relationship, and (iii) explain the relationship between grain and aerial dry matter yield for winter wheat and grain sorghum from a variety of field experiments conducted in the Southern High Plains.

The available data from this location were not sufficient to evaluate Eq. [1] as proposed by Gardner and Gardner (1983). Equation [1] should be more robust than Eq. [2] (plant basis compared to a field basis) since it will not have any dependence on plant density. This should be a fruitful area for future research.

MATERIALS AND METHODS

The data used in this analysis were taken from published experiments conducted at Bushland, TX (Table 1). In all experiments, either straw/grain ratio, straw or stover yield, or aerial dry matter yield data were reported along with grain yield data. The grain yield data were converted to an oven-dry basis from the reported grain water content. The straw/grain ratio was multiplied by the dry grain yield to determine the stover yield when only straw/grain ratio data were reported. The aerial dry matter yield was computed as the sum of the stover and dry grain yield. Standard linear regression analysis procedures were used to determine the intercept, slope, and coefficient of determination using the aerial dry matter yield (DM) as the independent variable and the dry grain yield (Y_d) as the dependent variable. The linear relationship was expressed by Eq. [2] with C' defined as the harvest index (HI) rather than the traditional definition of HI as Y_d/DM. The abscissa intercept (DM_o) was computed as the ratio of the negative value of the intercept to the slope. It is noted that the data used here represent the reported mean data from the experimental treatments resulting in some undetermined smoothing of the actual plot data.

RESULTS AND DISCUSSION

Grain Sorghum

Yield data from seven grain sorghum experiments at Bushland are shown in Fig. 2. These experiments contained a variety of main treatment effects such as tillage and residue management, fertility, water management (both irrigation and dryland studies with a variety of water deficit periods), soil profile modification, and crop cultural management (row spacing, seeding rates, etc.) and were conducted over many different growing season conditions. Also included in these experiments was a range of cultivars (Table 1). A linear relationship [Y_d = 0.47 (DM − 1.13)] explained over 95% of the variation in the grain yield data with a standard error of the estimate of 0.47 Mg

Table 1. Sources of Bushland data used in the analyses including the years of studies, main treatment, and cultivar under investigation.

Years of study	Cultivar	Main treatments	Source
Grain sorghum			
1956–1958	RS610	Row spacing, fertilizer, seeding rate	Porter et al. (1960)
1958–1959	RS610	Planting soil water, row spacing, seeding rate	Bond et al. (1964)
1965–1967	RS626 RS671	Soil Profile modification, irrigation	Eck and Taylor (1969)
1972–1978	DeKalb C42c C42y	Tillage and residue management	Unger and Wiese (1979)
1975	Pioneer 8311	Water deficit timing, irrigation	Eck and Musick (1979)
1977–1979	DeKalb C42y	Planting soil water, mulch rate	Unger and Jones (1981)
1983–1984	DeKalb 46	Row spacing, row orientation, seeding rate	Steiner (1986)
Winter wheat			
1955–1961	Concho	Irrigation, fertility	Jensen and Sletten (1965)
1971–1975	Tascosa	Tillage, irrigation	Unger (1977)
1977–1978	TAM 101 Vona	Planting date, irrigation	Musick and Dusek (1980)
1977–1981	TAM 101	Soil profile modification, irrigation	Eck (1986)
1979–1982	TAM 101 TAM 105 TAM 108 Triumph Concho Scout 66 Centurk 76 Sturdy	Irrigation	Musick (1984)
1980–1982	TAM 105	Irrigation, fertility	Eck (1988).

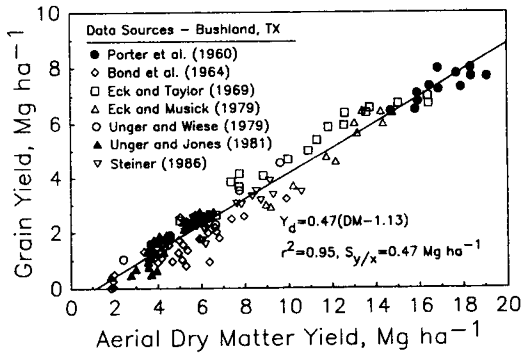

Fig. 2. Grain sorghum grain yield relationship to dry matter yield for several experiments conducted at Bushland, TX.

ha^{-1}. Both the intercept and slope values were significantly different ($P = 0.05$ level) from zero. The *HI* was 0.47 and DM_0 was 1.13 Mg ha^{-1}. It is noted that these values are representative of the mean plant densities of the various experiments and should be expected to vary with plant density as discussed in the introduction. These values are less than other reported values ($HI = 0.58$ and $DM_0 = 2.17$ mg ha^{-1}) by Slabbers et al. (1979), but agree with data for sorghum from Chauduri and Kanemasu (1985), for RS610 from a number of sites in Australia (Muchow et al., 1982), and for grain sorghum under salinity stress at several growth stages (Mass et al., 1986).

The partitioning of aerial dry matter into grain when defined by dY_d/dDM remains rather constant for grain sorghum across a wide variety of treatment effects. The linear regression results could be biased, particularly near DM_0, if sufficient data at the low yield values are not included in the data sets. A large threshold dry matter yield ($DM_0 = 1.13$ Mg ha^{-1}) for grain sorghum indicates that differences in the *HI* ratio (Y_d/DM) would not accurately indicate grain yield partitioning.

Winter Wheat

Data from five winter wheat experiments at Bushland are shown in Fig. 3. These experiments, like the grain sorghum experiments, contained a variety of main treatment effects including water management, critical water deficit timing, fertility, and soil profile modifications. These experiments were also conducted over a range of growing seasons and cultivars (Table 1). The simple linear relationship [$Y_d = 0.34(DM + 0.41)$] explained over 74% of the variation in the grain yield data with a standard error of the estimate of 0.63

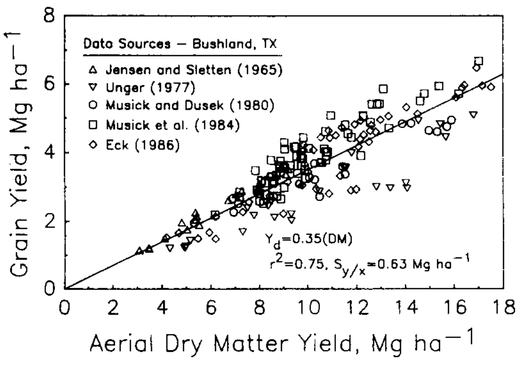

Fig. 3. Winter wheat grain yield relationship to dry matter yield for several experiments conducted at Bushland, TX.

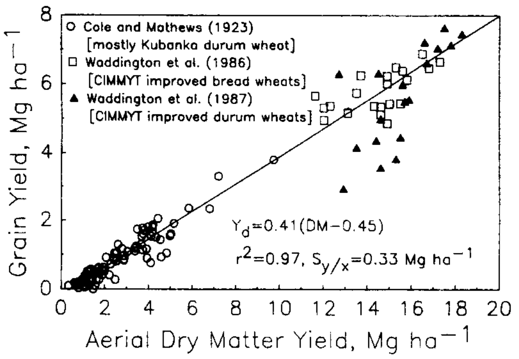

Fig. 4. Wheat grain yield-dry matter relationship from USDA dryland studies in the early 20th century and recent CIMMYT studies.

Mg ha^{-1}. The slope was significantly different (0.5 level) from zero, but the intercept (0.14 Mg ha^{-1}) was not significantly different (0.05 level) from zero. When the regression was forced through the origin, *HI* (slope) was 0.35 and DM_0 was then 0.0 Mg ha^{-1}. The scatter in the wheat data was much greater than for the grain sorghum data. Since few data values existed for very low grain yields, near zero, the value of DM_0 may be biased. The apparent reason for the larger scatter in the winter wheat data compared to the grain sorghum data could be related to either or both reduced kernel number and reduced kernel mass as affected by soil water deficits, particularly with dryland and limited irrigation treatments, and possibly temperature effects on grain filling duration at this location. Passioura (1977) illustrated large reductions in the *HI* ratio for wheat as the proportion of water use after anthesis decreased. Warrington et al. (1977) reported on the effects of temperature during different growth stages on wheat yields and high air temperatures could be expected to reduce the period of grain filling.

Figure 4 illustrates a grain-dry matter yield relationship based on data from the following areas: USDA dryland report (Cole and Mathews, 1923) for wheat (mostly Kubanka durum wheat) in the Southern High Plains; the Bushland area (Amarillo, TX, Dalhart, TX, and Tucumcari, NM); the High Plains to North Dakota; and from two recent studies [Waddington et al. (1986, 1987)] designed to examine the breeding advances in yield from bread and durum wheats, respectively, conducted at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico. The line illustrated in Fig. 4 is the linear regression for the data from Cole and Mathews (1923) and Waddington et al. (1986) only. This relationship explained over 97% of the variation in the two diverse data sets with a standard error of the estimate of 0.33 Mg ha^{-1}. Both the slope and intercept were significantly different (0.05 level) from zero. The resulting values for *HI* and DM_0 are 0.41 and 0.44 Mg ha^{-1}, respectively. The data from Waddington et al. (1987) for the improvement in the CIMMYT durum wheats (Fig. 4) clearly showed marked improvement in the *HI* ratio, but the *HI* ratio of later released cultivars remained close to the *HI* for Kubanka wheat grown early in the twentieth century on the Great Plains. The CIMMYT bread wheat data indicated that grain yield improvements resulting from the breeding developments are more likely due to increased dry matter yields than partitioning improvements or increases in

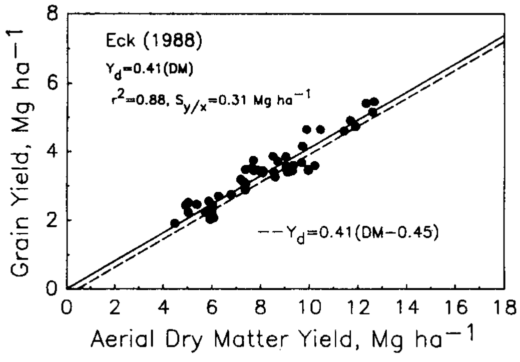

Fig. 5. Winter wheat grain yield-dry matter relationship from data of Eck (1988).

the *HI*. The values of *HI* and DM_0 for wheat derived from the Bushland studies are biased by the effects of (i) limited data near DM_0 to define the intercept point and (ii) effects of water and temperature effects on grain filling that, possibly, reduced grain yields.

The values for *HI* and DM_0 determined at Bushland for winter wheat are representative of data for spring wheat reported by Aase and Siddoway (1981) that showed *HI* (as defined by dY_d/dDM) varying from 0.43 to 0.48 for dryland and irrigated studies, respectively, while DM_0 varied from 0.19 to 0.21 Mg ha^{-1}, respectively. The simple linear relationship (Eq. [2]) explained over 94% of the variation in spring wheat grain yields from the 24 studies that Aase and Siddoway (1981) analyzed. Data from a recent study of irrigation and fertility effects on winter wheat yields at Bushland (Eck, 1988) (Fig. 5) closely fit the relationships in Fig. 4 and the upper bound of the data in Fig. 3. The data shown in Fig. 5 had a HI of 0.41 and a DM_0 of 0.0 Mg ha^{-1} with a coefficient of determination of 0.88 and standard error of the estimate of 0.31 Mg ha^{-1}. Again, the nonsignificant (0.05 probability level) intercept value of 0.17 Mg ha^{-1} for the data of Eck (1988) probably resulted from the lack of data at or near zero grain yield.

CONCLUSIONS

Estimation of grain yield for both grain sorghum and winter wheat should be improved by the use of Eq. [2] along with appropriate values of *HI* and DM_0 rather than assuming the *HI* ratio to be a species constant. The linear grain to dry matter yield relationship closely fits the majority of the data for grain sorghum at this location; however, DM_0 was more difficult to define for winter wheat and obviously much smaller than DM_0 for grain sorghum. The existence of DM_0 for grain sorghum indicates the difficulty in accurately estimating grain yield simply as the product of the *HI* ratio and the dry matter yield as widely suggested. The determination of the parameters *HI* and DM_0 in Eq. [2] requires an extensive range of data not normally found in a single experiment. The definition of *HI* as the slope, dY_d/DM, differs from the traditional definition as Y_d/DM, but permits a less biased determination (by linear regression) across a range of conditions rather than simply averaging many ratio values. Although the relationships presented here are strictly applicable to conditions similar to those from which the data were obtained (particularly the plant density), these relationships appear representative for a wider range of conditions (Fig. 4).

The consistent *HI* values for both winter wheat and grain sorghum at Bushland indicate the conservative (i.e., nearly constant) nature of photosynthate partitioning for these crops in this environment. The *HI* values for winter wheat and grain sorghum defined from a composite of experiments indicated small variations in *HI* from a large range in main treatments. The grain yield partitioning from the dry matter production as characterized by *HI* was more conservative (less variable) for grain sorghum at Bushland than for winter wheat. The large scatter in the winter wheat data (Fig. 3) at Bushland indicates that the treatment effects on grain yield partitioning from dry matter production may be larger for wheat than for grain sorghum. The dry matter threshold yield (DM_0) was larger for grain sorghum than for winter wheat indicating that the *HI* ratio (Y_d/DM) would more accurately indicate grain yield partitioning differences for wheat than for grain sorghum at this location.

The highly significant linear correlations between grain yield and aerial dry matter yield for both grain sorghum and winter wheat at Bushland indicate that the many main treatment effects in the experiments did not greatly affect grain yield partitioning from dry matter production despite large differences in yield caused by soil water deficits (including critical crop development periods), fertility, tillage, and many other treatment effects. Although the range of cultivars was limited to adapted regional varieties, the consistent value of *HI* indicates that breeding developments have not greatly increased *HI* at this location for either grain sorghum or winter wheat. Figure 3 indicates that the doubling of irrigated winter wheat grain yields at Bushland since the 1950s (Jensen and Sletten, 1965) from about 3 Mg ha^{-1} to current grain yields of 6 Mg ha^{-1} are due mainly to increased dry matter yields (increased from about 9 Mg ha^{-1} to 16 Mg ha^{-1}) and not increased *HI* (increased from about 0.38 to 0.40). This result contrasts with the reported hard red winter wheat breeding advances from the past 70 yr in Kansas under rainfed conditions reported by Cox et al. (1988). Sharma and Smith (1986) reported high linear correlations between Y_d and *DM* for winter wheat, poor correlations between HI ratio and *DM*, and suggested the use of either high HI ratio or high *DM* as a breeding selection criterion for wheat, largely in agreement with this conclusion.

REFERENCES

Aase, J.K., and F.H. Siddoway. 1981. Spring wheat yield estimates from spectral reflectance measurements. IEEE Trans. Geosci. Remote Sens. GE 19:78–84.

Bond, J.J., T.J. Army, and O.R. Lehman. 1964. Row spacing, plant populations and moisture supply as factors in dryland grain sorghum production. Agron. J. 56:3–6.

Chaudhuri, U.N., and E.T. Kanemasu. 1985. Growth and water use of sorghum [*Sorghum bicolor* (L.) Moench] and pearl millet [*Pennisetum americanum* (L.) Leeke]. Field Crop Res. 10:113–124.

Cole, J.S., and O.R. Mathews. 1923. Use of water by spring wheat on the Great Plains. Bur. Plant Industry Bull. no. 1004, USDA, Washington, DC.

Cox, T.S., J.P. Shroyer, L. Ben-Hui, R.G. Sears, and T.J. Martin. 1988. Genetic improvement in agronomic traits of hard red winter wheat cultivars from 1919 to 1987. Crop Sci. 28:756–760.

de Wit, C.T. 1958. Transpiration and crop yields. Inst. Voor Biologisch en Scheikundig Onderzoek van Landbouwgewassen, Verslagen van Landbouwkundige Onderzoekingen 64.6, Wageningen, The Netherlands.

Donald, C.M. 1962. In search of yield. J. Aust. Inst. Agric. Sci. 28:171–178.

Donald, C.M., and J. Hamblin. 1976. The biological yield and harvest index of cereals as agronomic and plant breeding criteria. Adv. Agron. 28:361–405.

Eck, H.V. 1986. Profile modification and irrigation effects on yield and water use of wheat. Soil Sci. Soc. Am. J. 50:724–729.

Eck, H.V. 1988. Winter wheat response to nitrogen and irrigation. Agron. J. 80:902–908.

Eck, H.V., and J.T. Musick. 1979. Plant water stress effects on irrigated grain sorghum. I. Effects on yield. Crop Sci. 19:589–592.

Eck, H.V., and H.M. Taylor. 1969. Profile modification of a slowly permeable soil. Soil Sci. Soc. Am. Proc. 33:779–783.

Gardner, W.R., and H.R. Gardner. 1983. Principles of water management under drought. Agric. Water Manage. 7:143–155.

Jensen, M.E., and W.H. Sletten. 1965. Evapotranspiration and soil moisture-fertilizer interactions with irrigated winter wheat in the Southern High Plains. USDA-ARS Conserv. Res. Rep. no. 4. U.S. Gov. Print. Office, Washington, DC.

Maas, E.V., J.A. Poss, G.J. Hoffman. 1986. Salinity sensitivity of

sorghum at three growth stages. Irrig. Sci. 7:1–11.
Monteith, J.L. 1977. Climate and efficiency of crop production in Britain. Philos. Trans. R. Soc., London B 281:277–294.
Muchow, R.C., D.B. Coates, G.L. Wilson, and M.A. Foale. 1982. Growth and productivity of irrigated *Sorghum bicolor* (L.) Moench in Northern Australia. I. Plant density and arrangement effects on light interception and distribution, and grain yield, in the hybrid Texas RS610 in low and medium latitudes. Aust. J. Agric. Res. 33:773–784.
Musick, J.T., D.A. Dusek, and A.C. Mathers. 1984. Irrigation water management of winter wheat. ASAE Paper no. 84-2094. ASAE, St. Joseph, MI.
Musick, J.T., and D.A. Dusek. 1980. Planting date and water deficit effects on development and yield of irrigated winter wheat. Agron. J. 72:45–52.
Passioura, J.B. 1977. Grain yield, harvest index and water use of wheat. J. Aust. Inst. Agric. Sci. 43:117–120.
Porter, K.B., M.E. Jensen, and W.H. Sletten. 1960. The effect of row spacing, fertilizer and planting rate on the yield and water use of irrigated grain sorghum. Agron. J. 52:431–434.
Sharma, R.C., and E.L. Smith. 1986. Selection for high and low harvest index in three winter wheat populations. Crop Sci. 26:1147–1150.
Slabbers, P.J., V.S. Herrendorf, and M. Stapper. 1979. Evaluation of simplified water-crop yield models. Agric. Water Manage. 2:95–129.
Snyder, F.W., and G.E. Carlson. 1984. Selecting for partitioning of photosynthetic products in crops. Adv. Agron. 37:47–72.
Steiner, J.L. 1986. Dryland grain sorghum water use, light interception, and growth responses to planting geometry. Agron. J. 78:720–726.
Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? p. 1–27. *In* H.M. Taylor et al. (ed.) Limitations to efficient water use in crop production. ASA, CSSA, and SSSA, Madison, WI.
Unger, P.W. 1977. Tillage effects on winter wheat production where the irrigated and dryland crops are alternated. Agron. J. 69:944–950.
Unger, P.W., and O.R. Jones. 1981. Effect of soil water content and growing season straw mulch on grain sorghum. Soil Sci. Soc. Am. Proc. 45:129–134.
Unger, P.W., and A.F. Wiese. 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. Soil Sci. Soc. Am. Proc. 43:582–588.
Versteeg, M.N., and H. van Keulen. 1986. Potential crop production prediction by simple calculation methods, as compared with computer calculations. Agric. Systems 19:249–272.
Waddington, S.R., J.K. Ransom, M. Osmanzai, and D.A. Saunders. 1986. Improvement in the yield potential of bread wheat adapted to northwest Mexico. Crop Sci. 26:698–703.
Waddington, S.R., M. Osmanzai, M. Yoshida, and J.K. Ransom. 1987. The yield of durum wheats released in Mexico between 1960 and 1984. J. Agric. Sci. (Camb.) 108:469–477.
Warrington, I.J., R.L. Dunston, and L.M. Green. 1977. Temperature effects at three development stages on yield of wheat ear. Aust. J. Agric. Res. 28:11–27.